

MAGNETIC FIELDS AND HALOS IN SPIRAL GALAXIES

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RESUMEN

Favor de proporcionar un resumen en español. If you are unable to translate your abstract into Spanish, the editors will do it for you. Radio continuum and polarization observations allow to reveal the magnetic field structure in the disk and halo of nearby spiral galaxies, their magnetic field strength and vertical scale heights. The spiral galaxies studied so far show a similar magnetic field pattern which is of spiral shape along the disk plane and X-shaped in the halo, sometimes accompanied by strong vertical fields above and below the central region of the disk. The strength of the halo field is comparable to that of the disk. While the total and turbulent magnetic field strength is (weakly) increasing with the star formation, we could not find such a correlation for the ordered magnetic field strength. On the contrary, there are indications that stronger star formation reduces the magnetic field regularity globally.

The magnetic field in spiral galaxies is generally thought to be amplified and maintained by dynamo action. Investigation of the large- and small-scale magnetic fields during the galaxy's formation and cosmological evolution lead to the picture that the turbulent dynamo amplifies the field strength to energy equipartition with the turbulent (small-scale) gas, while the large-scale (mean-field) dynamo mainly orders the magnetic field. Hence, the large-scale magnetic field pattern evolves with time. Supernova explosions causes a further continuous injection of turbulent magnetic fields. Assuming that this small-scale field injection is situated only within the spiral arm region where star formation mostly occurs lead to a large-scale field structure in which the magnetic field regularity is stronger in the interarm region as observed in several nearby spiral galaxies, sometimes even forming magnetic arms.

For several spiral galaxies of different Hubble type and different star formation rates and efficiencies we found similar scale heights of the total radio emission (300 ± 50 pc for the thin disk and 1.8 ± 0.2 kpc for the thick disk (halo)). This implies a relation between the galactic wind, the total magnetic field strength and the star formation in the galaxy. A galactic wind may be essential for an effective dynamo action. Strong tidal interaction, however, seems to disturb the balance leading to deviating and locally different scale heights as observed in M82 and NGC 4631.

ABSTRACT

Radio continuum and polarization observations allow to reveal the magnetic field structure in the disk and halo of nearby spiral galaxies, their magnetic field strength and vertical scale heights. The spiral galaxies studied so far show a similar magnetic field pattern which is of spiral shape along the disk plane and X-shaped in the halo, sometimes accompanied by strong vertical fields above and below the central region of the disk. The strength of the halo field is comparable to that of the disk. While the total and turbulent magnetic field strength is (weakly) increasing with the star formation, we could not find such a correlation for the ordered magnetic field strength. On the contrary, there are indications that stronger star formation reduces the magnetic field regularity globally.

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Key Words: galaxies: spiral — galaxies: magnetic fields — galaxies: halos — galaxies: star formation — galaxies: evolution — radio continuum: galaxies

1. INTRODUCTION

The effects of magnetic fields on the physical processes in spiral galaxies, their disk-halo interaction and their evolution have been frequently neglected in the past. Within the last 15 years, with increasing computing facilities, some authors included them in their simulations of e.g. the interstellar medium and disk-halo interaction (e.g. Korpi et al. (1999), Avillez & Breitschwerdt (2005)) or in the evolution of spiral galaxies (e.g. Pakmor & Springel (2013)). Their result is that magnetic fields play indeed an important role, even if the magnetic and cosmic ray energy density in the interstellar medium is small compared to that of the rotation. The magnetic field energy density is indeed comparable to that of the turbulent gas motion and much higher than that of the thermal gas as has been determined for the nearby galaxies NGC 6946 (Beck 2007) and M33 (Tabatabaei et al. 2008). Hence, magnetic fields are dynamically important in the processes of the interstellar medium. Direct comparison of 3-dimensional MHD simulations of an isolated galaxy with and without a magnetic field show that the magnetic field lead to a lower star formation rate at later times, it reduces the prominence of individual spiral arms and it causes weak outflows from the disk up to several kpc above and below the disk (Pakmor & Springel 2013).

Observationally, the magnetic field in external galaxies can best be studied in the radio continuum emission in the cm wavelength range. The total intensity of the synchrotron emission gives the strength of the total magnetic field. The linearly polarized intensity reveals the strength and the structure of the resolved regular field in the sky plane (i.e. perpendicular to the line of sight). However, the observed polarization vectors suffer Faraday rotation and depolarization (i.e. a decrease of the degree of linear polarization when compared to the intrinsic one) on the way from the radiation’s origin to us. Correction for Faraday rotation is possible with observations at different wavelengths by determining the rotation measure RM (being proportional to $\int n_e B_{\parallel} dl$ where n_e is the thermal electron density and B_{\parallel} the magnetic field strength parallel to the line of sight ¹). The rotation measure itself can be used to correct the observed polarization angle and also to estimate the strength of B_{\parallel} , its sign gives the direction of this magnetic field component. The field strength of both components, parallel and perpendicular to the line of sight, together with the information of the intrinsic

polarization vectors enables us in principle to get a three-dimensional picture of the magnetic field.

2. FARADAY ROTATION AND DEPOLARIZATION EFFECTS

While the polarized intensity gives the **orientation** of the magnetic field, the magnetic field **direction** can only be determined by the rotation measure. This implies that a large-scale regular (coherent) magnetic field can only be deduced from the rotation measure pattern, while the polarized intensity may also originate from anisotropic turbulent magnetic fields (e.g. compressed fields with opposite directions) in compressed or shocked regions. As the polarization is only sensitive to the magnetic field orientation, the polarization angle can only be determined with an $n \cdot \pi$ ambiguity. Further, depolarization effects have to be considered. We distinguish between wavelength-independent and wavelength-dependent depolarization. The difference in depolarization at different wavelengths in maps with the same linear resolution should be purely wavelength dependent where three different wavelength-dependent depolarization effects are important to consider: the differential Faraday rotation, Faraday dispersion, and a RM gradient within the beam (Burn 1966; Sokoloff et al. 1998). Faraday dispersion is due to turbulent (random) magnetic fields within the source and between the source and us, whereas differential Faraday rotation and depolarization by an RM gradient depends on the regular magnetic field within the emitting source. Especially differential Faraday rotation may cause that the source is not transparent in polarization if the internal Faraday rotation reaches values of 90° or more which may be the case for observations of spiral galaxies seen edge-on near the galactic midplane as e.g. in NGC 4631 (Mora & Krause 2013) even in the decimeter wavelength-regime. The coming polarization spectroscopy and RM-synthesis (Brentjens & de Bruyn 2005) will strongly reduce these effects.

3. MAGNETIC FIELD STRENGTH AND STAR FORMATION

The total magnetic field strength in a galaxy can be estimated from the nonthermal radio emission under the assumption of equipartition between the energies of the magnetic field and the relativistic particles (the so-called *energy equipartition*) as described in Beck & Krause (2005). The mean equipartition value for the total magnetic field strength for a sample of 74 spiral galaxies observed

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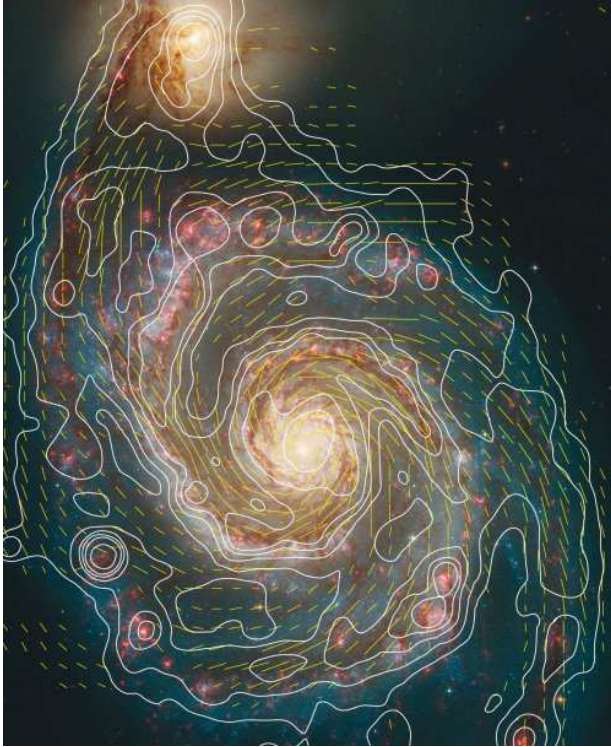


Fig. 1. Radio continuum emission of the spiral galaxy M51 at $\lambda 6.2\text{cm}$ (4.8 GHz) from VLA and 100-m Effelsberg observations with a resolution of $15''$ HPBW, overlaid on a Hubble Space Telescope optical image [image credit: NASA, ESA, S. Beckwith (STScI) and The Hubble Heritage Team (STScI/AURA)]. The contours give the total intensities, the vectors the apparent magnetic field orientation (i.e. not corrected for Faraday rotation) with their lengths being proportional to the polarized intensity (Fletcher et al. 2011).

by Niklas (1995) is on average $9 \pm 3 \mu\text{G}$ but reaches locally higher values *within* the spiral arms of up to $20 - 25 \mu\text{G}$ in M51 (Fletcher et al. 2011). The strength of the **ordered** magnetic fields in spiral galaxies are typically $1 - 5 \mu\text{G}$, and may reach locally values up to $10 - 15 \mu\text{G}$ as e.g. in NGC 6946 (Beck 2007) and M51 (Fletcher et al. 2011). The field strengths in the halo are comparable to the those in the disk (see Sect. 4).

The **turbulent** magnetic field is typically strongest within the optical spiral arms, whereas the regular fields are strongest in between the optical spiral arms, or at the inner edge of the density-wave spiral arm as seen in M51 (Fletcher et al. 2011) (Figure 1). Sometimes, the interarm region is filled smoothly with regular fields, in other cases the large-scale field form long filaments of polarized intensity like in IC342 (Figure 2) (Krause 1993) or so-called *magnetic spiral arms* like in NGC 6946 (Beck et al.

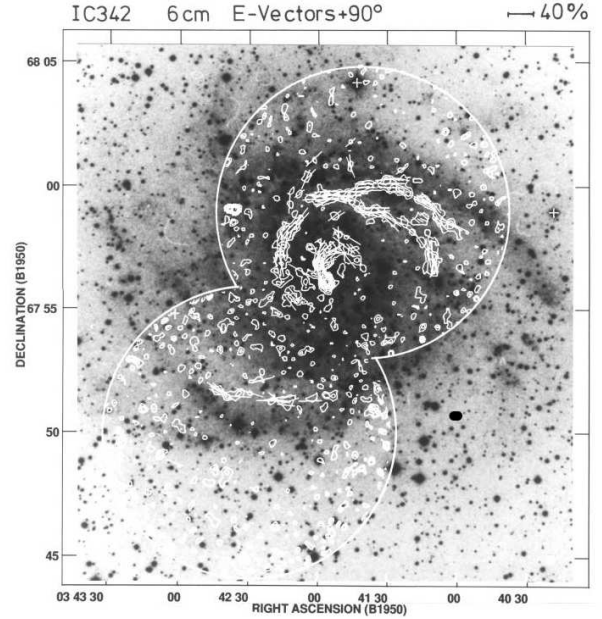


Fig. 2. Radio continuum emission of the spiral galaxy IC342 at $\lambda 6.2\text{cm}$ (4.8 GHz) from VLA observations with a resolution of $16''$ HPBW, overlaid on a POSS optical image. The contours give the polarized intensities, the vectors the apparent magnetic field orientation with their lengths being proportional to the degree of polarization (Krause 1993).

1996).

Strongly interacting galaxies or galaxies with a high star formation rate (SFR) tend to have generally stronger total magnetic fields. The latter fits to the equipartition model for the radio-FIR correlation Niklas & Beck (1997), according to which the nonthermal emission increases $\propto \text{SFR}^{1.3 \pm 0.2}$ and the *total*, mostly turbulent magnetic field strength B_t increases $\propto \text{SFR}^{0.34 \pm 0.14}$.

No similar simple relation is known for the *ordered* magnetic field strength. We integrated the polarization properties in 41 nearby spiral galaxies and found that (independent of inclination effects) the degree of linear polarization is lower ($< 4\%$) for more luminous galaxies, in particular those for $L_{4.8} > 2 \times 10^{21} \text{ WHz}^{-1}$ Stil et al. (2009). The radio-brightest galaxies are those with the highest SFR. Though dynamo action needs star formation and supernova remnants as the driving force for velocities in vertical direction, we conclude from our observations that stronger star formation reduces the magnetic field regularity. On kpc-scales, Chyży (2008) analyzed the correlation between magnetic field regularity and SFR locally within one galaxy, NGC 4254. While he found that the total and

random field strength increase locally with SFR, the ordered field strength is locally uncorrelated with SFR.

4. MAGNETIC FIELD STRUCTURE IN SPIRAL GALAXIES

Observations of spiral galaxies seen face-on reveal a large-scale magnetic field pattern along the plane of the galaxy. The magnetic field lines generally follow a spiral structure with pitch angles from 10° to 40° which are similar to the pitch angles of the optical spiral arms, as visible e.g. in (Figure 1). This large-scale pattern is accompanied by a small-scale magnetic field which is stronger within the optical spiral arms. The magnetic field is thought to be amplified and maintained by dynamo action, especially the large-scale structure by the action of the mean-field dynamo (Ruzmaikin et al. 1988) which predicts an axisymmetric mode (ASS) along the galactic plane of the galaxy to be excited most easily. The mean-field dynamo theory alone, however, cannot explain why the strength of the large-scale magnetic field is higher in the interarm region as discussed in Sect. 3. This will further be discussed in Sect. 5. The mean field theory also cannot explain why the magnetic pitch angles are similar to the pitch angles of the optical spiral arms (as summarised in Fletcher 2010). Within the dynamo theory the magnetic pitch angles are simply determined by the ratio of the radial to the azimuthal magnetic field components ($p = \arctan B_r/B_\varphi = -\sqrt{R_\alpha/R_\omega}$, see also Sect. 5) (Ruzmaikin et al. 1988), whereas the spiral arm pitch angle may even be related to the supermassive black hole mass (Seigar et al. 2008).

Observation of spiral galaxies seen edge-on show in general a plane-parallel magnetic field structure along the midplane which is the expected projection of the spiral field in the disk as observed in face-on galaxies. This is also the case in NGC 4631 as detected by Mora & Krause (2013).

In the halo the ordered magnetic field is X-shaped as indicated in the sketch for NGC 5775 observed with an inclination $i = 86^\circ$ (Figure 3). In some galaxies the X-shaped halo field is accompanied by strong vertical components above and/or below the central region as in NGC 5775 (Figure 3) and NGC 4631 (Figure 4). Reliable RM values of the X-shaped field in the halo are still missing, hence we cannot decide observationally whether these are regular or anisotropic turbulent fields. They can also be a mixture of both.

In general the strength of the ordered halo field is comparable to the strength of the large-scale disk field. It cannot be explained by the classical mean-field dynamo operating in the disk. Even though this is also accompanied by a poloidal halo field, this is by a factor of about 10 weaker than the observed halo field. Either there is also dynamo action in the halo or a galactic wind is needed to transport magnetic field from the disk into the halo. This will be further discussed in Sect. 6

5. DYNAMO ACTION AND THE EVOLUTION OF THE LARGE-SCALE MAGNETIC FIELD

The large-scale magnetic field can only be amplified and maintained by dynamo action. While a large-scale dynamo is necessary to produce a large-scale magnetic field structure, field amplification alone is faster by the action of a small-scale dynamo (Beck et al. 1994, 1996). For a galactic disk, the large-scale dynamo is the $\alpha\Omega$ -dynamo, simplified by the mean-field dynamo equations. Solution of these equations are the large-scale dynamo-modes, with the axisymmetric spiral field structure (ASS) being the dominant mode ($m=0$) which is generated easiest, followed by the bisymmetric structure (BSS, $m=1$) and higher modes. The 3-dimensional field configurations can be either symmetric (of quadrupole type) or asymmetric (of dipole type) with respect to the galactic plane, where the poloidal field component is about a factor of 10 weaker than the disk field. According to the dynamo theory the pitch angle of the magnetic field spiral is determined by the dynamo numbers R_α and R_ω , not by the pitch angle of the gaseous spiral arms. The modes determined observationally in a dozen of nearby galaxies and their relative amplitudes are summarised by Fletcher (2010). The dominating mode in the disk is indeed the ASS.

As part of the SKA design study we investigated the large- and small-scale dynamo action and the ordering process of the large-scale magnetic field structure during galaxy formation and cosmological evolution (Arshakian et al. 2009). Turbulence generated in protogalactic halos by thermal virialization can drive an effective turbulent (small-scale) dynamo which amplifies the field strength to energy equipartition with the turbulent gas (beginning at $z \approx 10$ in Figure 5). The large-scale dynamo mainly orders the magnetic field with timescales determined by the mean-field dynamo theory. Hence, the large-scale fields evolve with time. Galaxies similar to e.g. the Milky Way formed their disks at $z \approx 10$. Regular

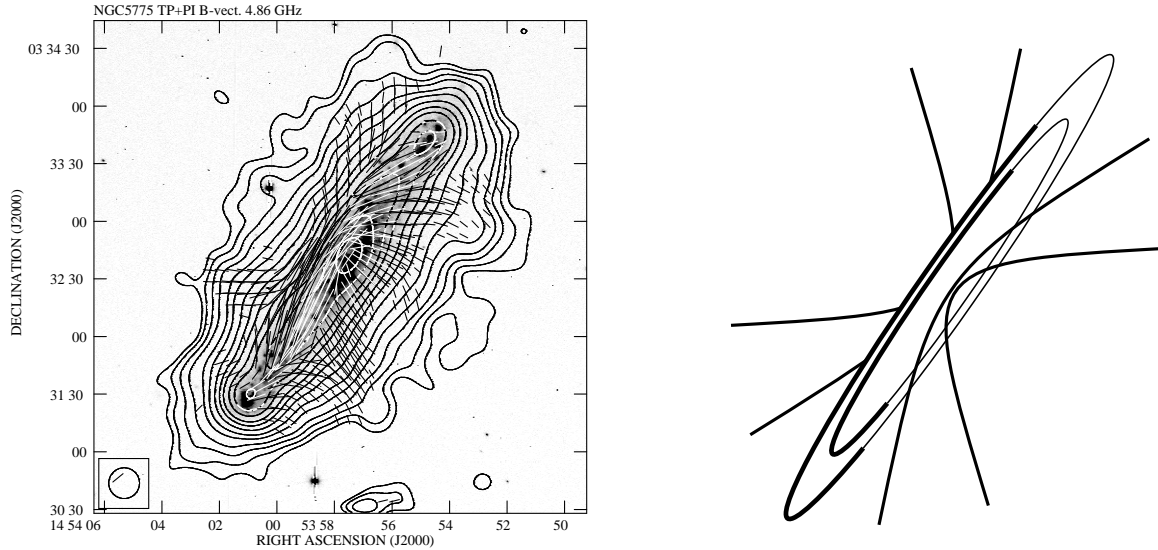


Fig. 3. Total intensity contours map with apparent magnetic field orientation at 4.8 GHz of NGC 5775 (from the VLA with a resolution of $16''$ HPBW) overlaid on an $H\alpha$ image (left) and sketch of the regular magnetic field configuration in the disk and in the halo (right) (from Soida et al. 2011).

fields of μG strength and a few kpc coherence length were generated within 2 Gyr (beginning at $z \approx 20$ in Figure 5), but field ordering on the coherence length of the galaxy size requires additional 6 Gyr for Milky-Way-type galaxies. Dwarf galaxies can already host fully coherent fields at $z \approx 1$ while giant disk galaxies may not have reached fully coherent field pattern in the Universe's lifetime up to now (Arshakian et al. 2009).

Arshakian et al. (2011) studied the field ordering of a so-called “spotty” magnetic field structure in more detail assuming that the large-scale dynamo starts from coherent fields in spots of 100 pc in size and $0.02 \mu\text{G}$ in strength. The evolution of these magnetic spots is simulated in a model. A star formation in a galaxy causes -via supernova explosions- a continuous injection of turbulent magnetic fields. Moss et al. (2012) combined the interaction of magnetic fields generated by small-scale dynamo action in discrete star formation regions together with the mean-field dynamo action. Assuming that the injection of small-scale fields is situated only within the gaseous spiral arm regions where star formation mostly occurs, Moss et al. (2013) obtained field structures with magnetic arms located between the spiral arms as discussed in Sect. 3 (see Figure 6).

6. VERTICAL SCALE HEIGHTS AND GALACTIC WIND

We determined the vertical scale heights of the total power radio emission in several edge-on

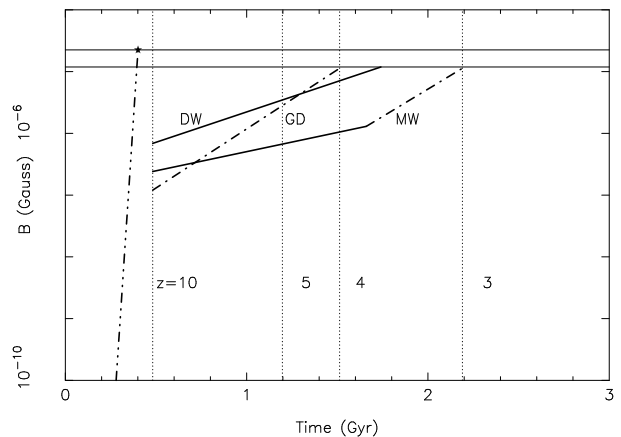


Fig. 5. Evolution of magnetic field strength in dwarf galaxies (DG), Milky-Way-type galaxies (MW), and in giant disk galaxies (GD). The thick dashed-dot-dot-line shows the evolution of the small-scale magnetic field generated by the small-scale dynamo. The evolution of the large-scale magnetic field generated by the mean-field dynamo in quasi-spherical galaxies are shown by the thick solid line and that in thin-disk galaxies as thick dashed-dot dashed-lines (Arshakian et al. 2009).

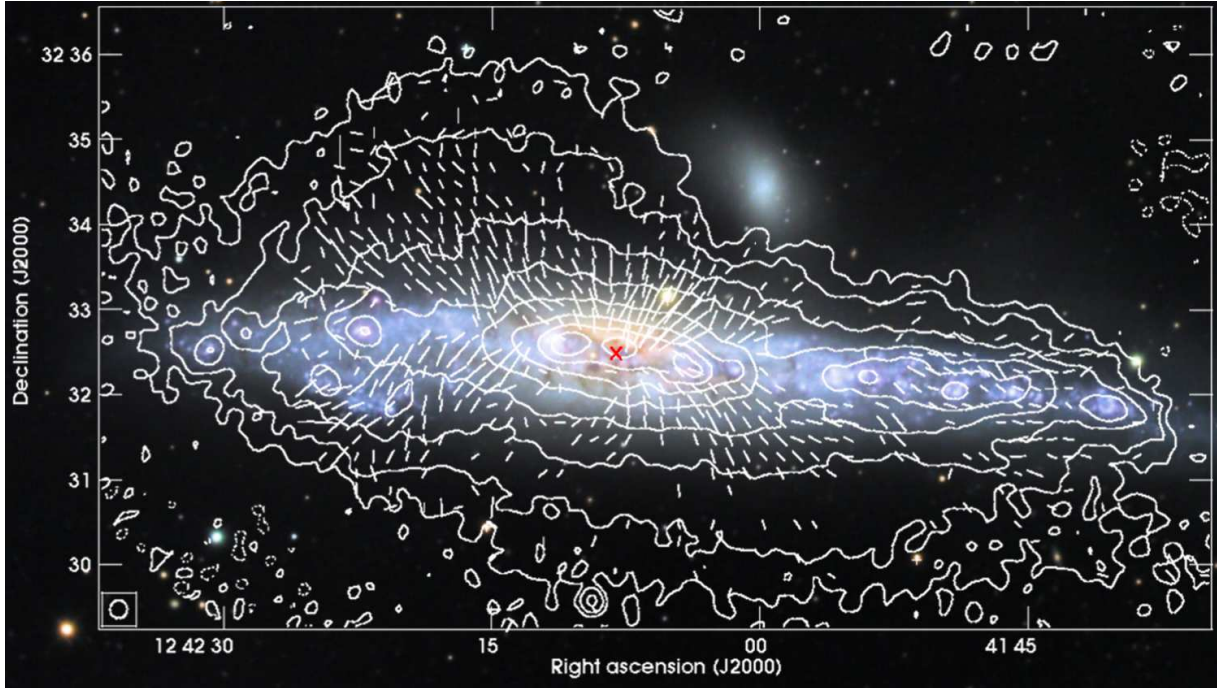


Fig. 4. Radio continuum emission of the edge-on spiral galaxy NGC 4631 at $\lambda 6.2\text{cm}$ (8.4 GHz) from VLA and 100-m Effelsberg observations with a resolution of $12''$ HPBW, overlaid on a colour-scale optical DSS image. The contours give the total intensities, the vectors the apparent magnetic field orientation with their lengths proportional to the polarized intensity (Mora & Krause 2013).

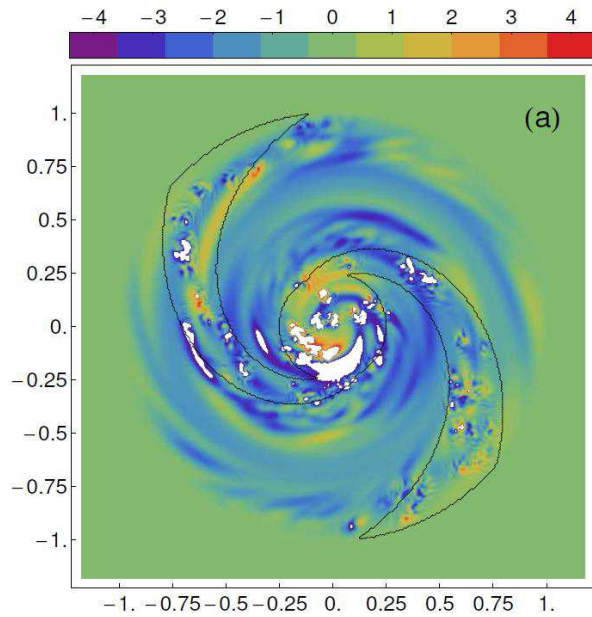


Fig. 6. Colour coded image of the modeled azimuthal magnetic field strength in the disk of a spiral galaxy with turbulent magnetic field injection assumed within the normal spiral arm regions as indicated by the thin black lines after 13.2 Gyr. The field strength is given in μG (Moss et al. 2013).

spiral galaxies. The results are summarized in Tab. 1. For all galaxies except M104 (NGC4594) a (two-component) exponential fit was better than a gaussian fit. For the first 5 galaxies in Tab. 1 and for NGC 4631 single-dish (100-m Effelsberg) and interferometer (VLA) data were merged in order not to miss extended flux because of missing spacings. The scale heights were determined from $\lambda 6$ cm observations except for NGC 5907 (observed at $\lambda 20$ cm). At $\lambda 6$ cm the vertical *scale heights* of the thin disk and the thick disk/halo in the sample of the first five galaxies in Tab. 1 are similar and have a mean value of 300 ± 50 pc for the thin disk and 1.8 ± 0.2 kpc for the thick disk. This sample of galaxies include the one with the brightest halo observed so far, NGC 253, with strong star formation, as well as one of the weakest halos, NGC 4565, with weak star formation. The SFR-values were determined directly from the IR-emission given by Young et al. (1989) according to Kennicutt (1998), the SFE-values in Tab. 1 were determined from values for the molecular masses given in the literature.

If synchrotron emission is the dominant loss process of the relativistic electrons the outer shape of the radio emission should be dumbbell-like as the local

TABLE 1

VERTICAL SCALE HEIGHTS, STAR FORMATION RATES (SFR) AND EFFICIENCIES (SFE),
AVERAGED TOTAL MAGNETIC FIELD STRENGTHS B_t , INCLINATION i AND HUBBLE-TYPE FOR
OUR SAMPE OF EDGE-ON SPIRAL GALAXIES^a

galaxy	Vertical scale heights		SFR(IR) [$M_\odot \text{yr}^{-1}$]	SFE [$L_\odot M_\odot^{-1}$]	B_t [μG]	i [$^\circ$]	Hubble type	References for scale heights
	thin disk [pc]	thick disk [kpc]						
NGC253	380 ± 60	1.7 ± 0.1	6.3	14	12	78	Sc	Heesen et al. 2009a
NGC891	270	1.8	3.3	5.0	6	88	Sb	Dumke & Krause 1998
NGC3628	300	1.8	1.1	4.9	6	89	Sb pec	Dumke & Krause 1998
NGC4565	280	1.7	1.3	3.2	7	86	Sb	Dumke & Krause 1998
NGC5775	240 ± 30	2.0 ± 0.2	7.3	6.1	8	86	Sbc	Soida et al. 2011
mean	300 ± 50	1.8 ± 0.2						
NGC5907	340	≥ 1.5	1.3	4.0	5	87	Sc	Dumke et al. 2000
M104	1.4 \pm 0.2 gaussian		1.2	4.2	4	84	Sa	Krause et al. 2006
NGC4631	370 ± 280	2.3 ± 0.9	2.1	9.9	6	86	SBd	Mora & Krause 2013
M82	see text in Sect. 6		1.8	22	35	79	SBc	Adebahr et al. 2013

^aThe vertical scale heights are determined from 4.8 GHz data except for NGC 5907 (at 1.4 GHz). The 4.8 GHz observations for the first five galaxies and NGC 4631 are merged single-dish (100-m Effelsberg) and interferometer (VLA) data.

scale height depends on the local magnetic field strength. In fact, a dumbbell shape of the total radio intensity has been observed in several edge-on galaxies like e.g. NGC 253 (Heesen et al. 2009a) and NGC 4565. As the synchrotron lifetime t_{syn} at a fixed frequency is proportional to the total magnetic field strength $B_t^{-1.5}$, a cosmic ray bulk speed (velocity of a galactic wind) can be defined as $v_{CR} = h_{CR}/t_{syn} = 2h_z/t_{syn}$ in the case of equipartition, where h_{CR} and h_z are the scale heights of the cosmic rays and the observed radio emission at this frequency. For NGC 253 Heesen et al. (2009a) determined the cosmic ray velocity to 300 ± 30 km/s in the north-eastern halo. As this is similar to the escape velocity, it shows the presence of a galactic wind in NGC 253. Further, the similarity of the observed radio scale heights suggest a self regulation mechanism between the galactic wind velocity, the total magnetic field strength and the star formation rate SFR in the disk: $v_{CR} \propto B_t^{1.5} \propto SFR^{0.5}$ where the relation between B_t and SFR refer to the equipartition model for the radio-FIR relation (Niklas & Beck 1997).

The scale heights in NGC 5907 are measured from $\lambda 20$ cm observations taken with the VLA (Dumke et al. 2000). They are similar to the values of the sample of 5 galaxies discussed above. If synchrotron losses dominate in this galaxy, its scale heights are expected to be somewhat larger than

those at $\lambda 6$ cm, however the maps may suffer large extended structure (Dumke et al. 2000).

The Sombrero galaxy M104 is classified as an Sa galaxy and shows a huge bulge with an elliptical mass distribution. The expected z-distribution of a relatively thin layer (the disk) inside a nearly spherical gravitational potential is in fact a Gaussian (Combes, 1991). The bulge in M104 may be due to a dissolving bar as proposed by Emsellem, 1995.

Recent determination of the scale heights in M82 and NGC 4631 also yielded different values: the scale heights in M82 are by a factor of ≈ 3 smaller than the mean values mentioned above. The scale heights in the north are larger than those south of the disk (Adebahr et al. 2013). The scale heights for both, the thin and thick disk in NGC 4631 vary strongly within the galaxy being significantly larger in some areas than the mean values in Tab. 1 (Mora & Krause 2013). Both galaxies show -different to the first five galaxies in Tab. 1- strong signs of tidal interaction like HI tails and bridges (Yun et al. 1993; Rand 1994) where M82 might even have lost its outer HI disk by tidal disruption. Hence, from present observations of edge-on galaxies we conclude that while star formation and even starbursts in the disk alone do not significantly change the scale heights of the disk and halo, (strong) tidal interactions may well modify these parameters.

The observations of similar scale heights for not strongly interacting galaxies (the first five galaxies in Tab. 1 and probably NGC 5907 as well) suggest the existence of a galactic wind in all of them. It may be essential for the formation of large-scale magnetic field in the halo as discussed in Sect. 4. Indeed, model calculations of the mean-field $\alpha\Omega$ -dynamo for a disk surrounded by a spherical halo including a galactic wind (Brandenburg et al. 1993; Moss et al. 2010) simulated similar magnetic field configurations to the observed ones. Meanwhile, MHD simulations of disk galaxies including a galactic wind implicitly may explain the X-shaped field (Gressel et al. 2008; Hanasz et al. 2009a). The first global, galactic scale MHD simulations of a CR-driven dynamo give promising results resembling the observations and show directly that small scale magnetic flux is transported from the disk into the halo (Hanasz et al. 2009b). A galactic wind can also solve the helicity problem of dynamo action (e.g. Sur et al. 2007). Hence, a galactic wind may be essential for an effective dynamo action and the observed X-shaped magnetic field structure in edge-on galaxies.

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